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TECHNOLOGIES TO DEVELOP TECHNOLOGY:THE IMPACT OF NEW TECHNOLOGIES ON THE ORGANISATION OF THE INNOVATION PROCESS

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Technologies to develop technology:
The impact of new technologies on the organisation of the innovation process

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0. Abstract

Companies are under increasing pressure to develop new products more effectively and efficiently. In order to meet this challenge, the organisation of the new product development process has received ample attention both in the academic literature and in the practitioner literature. As a consequence, a myriad of methods to design new products has been developed. These methods aim at facilitating concurrent product design and engineering. However, it is only recently, through the advent of families of new design technologies, that concurrency really becomes possible. In this paper, research on the impact of new design technologies on the product development process is reported and discussed. It is demonstrated that these technologies can have a significant impact on the organisation of innovation processes.

1. Technology and the black box of innovation

This paper is about the ways in which companies develop technological innovations that become embedded into products and processes. More specifically, we want to discuss the way new technologies such as 3D CAD systems or 3D prototyping technologies, commonly known as parametric design technologies, are shaping and reconfiguring the organisation of the innovation process. As a consequence, this paper is first of all concerned with innovation operations. Only through an in-depth understanding of these operations is it possible to gradually open the black box of technology development. However, this does not mean that these operations are devoid of strategic significance. We therefore will conclude the discussion by showing how the integration of these innovation operations into an "Integrated Design Capability" can sustain a firm's competitive position, and hence, turn innovation into a strategic weapon for the company.

1.1. Understanding technology

Technology has always been omnipresent in innovation management research and practice. Understanding the genesis and the evolution of new technologies is indeed necessary if one is to open the "black box" of the technological innovation process.

Technological innovation is hereby defined as the successful commercial exploitation of inventions as they become embodied into new products and processes. The emphasis thus is on exploiting the results of technological creativity and activity, by integrating them into products and processes. There are, of course, different opinions on what constitutes a "new" technology, product or process.

In the most pure sense, the technology, the product or the process developed is new to the world. This need not be the case, though. A technology, product or process can indeed be new to the company without it being new to the world. Current definitions of technological innovation even go further by including improvements to existing products or processes as innovations. In sum, we can and should go as far as considering any product or process an innovation as long as it is perceived as new to the organisations involved, even though it may appear to others to be an "imitation" of something that exists elsewhere (Van de Ven, 1986).

It is obvious that any company involved in innovation should be aware of this full and broad spectrum of innovative activity. The distribution of degrees of newness in a firm's innovative endeavours lays at the origins of the concept of the innovation portfolio (Roussel, Saad & Erickson, 1991). This variety in degrees of newness is important to spot familiarity gaps with respect to a firm's established expertise and experience base. The higher the degree of newness of an innovation, the higher the chance is that the firm lacks some critical expertise or experience to make the innovation successful. Hence, the higher the chance for failure and/or the higher the need for the firm to attract expertise and experience that is external to the firm.

In those instances, we truly have to consider make-and-buy decisions rather than mere make-or-buy decisions, as the firm has to internalise and to develop absorptive capacity to sustain this type of innovation (Debackere, Clarysse & Rappa, 1996a&b). For instance, a software developer that has a lifelong expertise and experience designing and developing programs in an IBM AS400 environment may find it impossible to develop a software package running on a UNIX platform solely by relying on current in-house capabilities. Just buying the expertise externally may be insufficient, as the developer will have to gain fluency and experience with the new programming environment if it truly wants to integrate UNIX in its product range. Hence, the buy decision needs to complement rather than to substitute the make decision. Along similar lines, banks that have developed a wide array of software applications in the by now traditional COBOL environment will face at least some turbulence (and need for new capabilities) as they switch to object oriented programming.

At the same time, this need for new capabilities is often offset by the inertia emerging from the firm's established skill base (Debackere, Clarysse & Rappa, 1996c; Henderson & Clark, 1990; Katz & Allen, 1982). This inertia operates not only at the level of organisational routines, but also in the minds, beliefs and search heuristics of the practitioners shaping technological progress. These practitioners, engineers and scientists, are at the basis of the existence of communities of practitioners that create, shape, but also inhibit, technological development as they build momentum and at the same time generate inertia (Constant, 1980; Debackere & Rappa, 1994).

Moreover, the "newness" of an innovation may not only enhance but can also disrupt the firm's current technical and market capabilities as well as its established relationships with professional communities and supplier/customer communities (Abernathy & Clark, 1985). This distinguishes innovation management from quality management as the latter one is geared toward continuous improvement. Innovation management is not only about managing improvement via continuity, but also about managing discontinuous change within the firm in order to sustain the (future) continuity of the firm. "Newness" therefore introduces risk, uncertainty and ambiguity at various levels depending on the very nature of newness itself. Managing innovation therefore boils down to managing and coping with newness, including the inherent uncertainty and ambiguity.

The Cyclone Converter Furnace (CCF) developed by Koninklijke Hoogovens is a good example of an innovation that disrupts existing competencies. The CCF process is a two-stage process that consists of pre-reduction and pre-melting of ore in a melting cyclone followed by final reduction in a converter type vessel containing a liquid iron bath. Both stages of the process are combined in a single reactor. The CCF produces hot metal directly from the raw materials. The carbonisation of coal and the agglomerations of ores are no longer required (Meijer, Flierman, Teerhuis, Bernard & Boom, 1995). This process, once fully operational, will put an end to the "thousand-year" realm of the blast furnace. For a company named "Koninklijke Hoogovens" *(literal translation: Royal Blast Furnaces)*, this example illustrates all too well what I mean by competence disruption. It does not only mean changing competencies but also, at least to some extent, changing identity. And, it must be a very strong organisation that is able to violate and to replace its well-established routines.

To conclude, the higher the disruptive character of the innovation, the more challenges an organisation will experience to turn the innovation into a commercial success. Both the acquisition and the development of organisational capabilities as well as grasping the "fit" between the innovation and its context of use, take on a more demanding perspective in the face of competence disrupting innovations. As we will see later on in this paper, introducing new design technologies to sustain the innovation process most often has a similar disruptive impact on the established design and development practice in many organisations. But, before turning to this design revolution, let us first have a look at the nature of the process of technological product creation.

1.2. The design hierarchy: managing "form" and "context"

At the roots of each new product development lies a design hierarchy, including a technology tree (e.g. Clark, 1985; Iansiti, 1997; Ulrich & Eppinger, 1995). This design hierarchy does not come about at random. It is the result of two related processes. The first process reflects the logic of technical problem solving in product design (e.g. Allen & Frischmuth, 1969; Petroski, 1996; Weber and Perkins, 1992). The second process is the formation of product concepts that underpin and fulfil customer needs (e.g. Cooper, 1993; Cooper & Kleinschmidt, 1996; ReVelle, Moran & Cox, 1998; Souder, 1987; Thomas, 1993; von Hippel, 1988). The presence and the interaction of both processes impose a hierarchical structure on product-technology evolutions.

The presence of a design hierarchy is thus at least partly due to the internal (problem solving) logic of the design itself. As suggested by Petroski in his 1996 book "Invention by Design", design is a process of understanding what the product's form is and how it might "fit" the context in which it is to function. The outcome of the design process is the result of cycles of experimentation and analysis that gradually define and refine the form of the product. Components are identified, major systems and sub-systems are conceptualised and chosen, and their interrelationships are examined. Physical, chemical, mechanical, electrical and other engineering "laws" impose specific constraints on the form of the design hierarchy, which can therefore be conceptualised as a "decision" tree. This form of the product can further be thought of as a set of technical specifications and requirements (Gevirtz, 1994; ReVelle, Moran & Cox, 1998).

However, form is not sufficient. As mentioned, the task at hand is to choose design concepts for functional parameters that result in a form that "fits" the context well. Goodness of fit between form and context therefore is at the heart of the second process shaping a design hierarchy. The "fit" of the product form with its context is most often conceptualised as a set of functional specifications or requirements (Gevirtz, 1994; ReVelle, Moran & Cox, 1998). As we will see later on, methodologies like Quality Function Deployment attempt at aligning form and context precisely by linking those technical and functional parameters (Bossert, 1991; Hauser & Clausing, 1988; Debackere, Van Looy and Vliegen, 1997). Thus, the cycles of experimentation and analysis referred to previously are necessary to develop a "form" that is aligned to its "context of use."

A cellular phone is the outcome of the integration of many different technologies, embodied in components and subassemblies that are ultimately assembled into the by now familiar phone set. The Bill-of-Material of a cellular phone is perhaps the most visible and tangible outcome of a design hierarchy that captures the "form" of the product. However, from an innovation perspective, "form" alone is not sufficient. The form is based on technical parameters that should fit the context of use, as described by the product's functional parameters.

In the example of a cellular phone, some relevant functional parameters are: the weight of the phone, its volume and dimensions, the price of the phone, its memory size, the voice mail functionality, the positioning of the phone ("business" versus "consumer"), the battery performance, and the design aesthetics of the phone. These functional parameters define the context of use of the phone. Besides delineating the functional parameter space, it is critical to define the value of those parameters once this space is defined. Both the definition of the parameter space and the assessment of the target values of the functional parameters define the fit of the product form to its context of use.

However, in defining those functional parameters, we have to take into account technical constraints as they emerge from physical and engineering limitations. For instance, the functional parameters like weight, volume and price will be determined by technical parameters such as the number and the type of discrete components used the technical parameters for EMI (radiation) shielding, the technical characteristics of the battery pack, etc. Aligning form to context thus implies aligning functional and technical requirements. As has been argued many times (e.g. Twiss, 1994; Van de Ven, 1986), achieving this alignment is not at all a linear and a sequential process. But, most often it is the result of a coupled process in which different groups within the company and even outside the company have to interact and to iterate. This iterative process is at the origins of the design hierarchy referred to at the beginning of this section: starting from a high level design to iterate toward a more detailed level design including subassemblies, subcomponents and basic design parts. As I will explain in more detail later on, the specific details of this design hierarchy are filled out during cycles of experimentation and analysis.

Of course, when referring to cellular phones, product technology is just one half of the technological Janus face. Process technology is the other half. The components, subassemblies and final assemblies all need to be manufactured in a timely and a cost-effective manner (Kalpakjian, 1995). It is obvious that the process requirements and limitations also have an impact on the development of the design hierarchy just described. As a consequence, product and process technology have to be taken into account in fitting form to context, thus further increasing the complexity of the product design. Because of this complexity, both product and process data management have become increasingly important in the design and the development of new products. Software technologies to manage libraries of product and process data (e.g. the CADIM software) therefore become an increasingly important support tool in designing new products. As suggested by Abernathy and Utterback in their dynamic model of product and process innovation (1978) as well as by Van de Ven (1986) in his coupled model of the innovation process, there not only has to be an intimate coupling between product "form" and "context of use," but also between product and process parameters.

1.3. Uncertainty and ambiguity: mediating the "fit" between form and context

In fitting "form" to "context," ambiguity and uncertainty play a central role (Debackere, 1998; Schrader, Riggs & Smith, 1993; Van Looy, Debackere & Bouwen, 1999). Although both concepts are related, they are not completely overlapping. Ambiguity and uncertainty, therefore, both play a distinct role in designing and developing products and product applications. However, this distinctive role has been to a large extent neglected in the many models that provide guidance in managing the innovation process.

Reducing levels of uncertainty has indeed been the primary concern in many conceptual models and techniques that attempt at providing insights to manage the innovation process. Uncertainty is characteristic of a situation in which the problem solver considers the structure of the problem (including the set of relevant variables) as given, but is dissatisfied with the knowledge available of the value of these variables.

This is in line with both information theory and decision theory that have defined uncertainty as characteristic of situations where the set of possible future outcomes is identified, but where the related probability distributions are unknown, or at best known subjectively. Decision theory also defines the concept of risk as a special case of uncertainty. That is, risk is uncertainty with known probabilities.

Research on organisations has broadened those definitions to fit the organisational context. Galbraith (1973) defines uncertainty as the difference between the information an organisation has and the information it needs. This coincides with the early definitions of uncertainty provided by researchers on the psychology of problem solving (e.g. Miller & Frick, 1949), as derived from the mathematical theory of communication (Shannon & Weaver, 1949). Duncan (1972) defines uncertainty as follows:

> "(1) The lack of information regarding environmental factors associated with a given decision-making situation, (2) not knowing the outcome of a specific decision in terms of not knowing how much the organisation would lose if the decision were incorrect, and (3) inability to assign probabilities with any degree of confidence with regard to how environmental factors are going to affect the success or failure of the decision unit in performing its function."

The first two components are quite similar to the broad definition by Galbraith (1973), while the third component is similar to the more narrow definitions that stem from information and decision theory. The common theme behind all those definitions is that uncertainty is related to asymmetric and lack of information. Consequently, if problem solvers want to reduce uncertainty, they should gather information on variables that are known to them.

This finding then has been at the heart of many models and instruments designed to manage the innovation process, which is in essence a process of uncertainty reduction through problem solving activity (Allen, 1977; Brown & Eisenhardt, 1995).

Uncertainty reduction has thus been a central theme in many seminal writings on the need for cross-functional integration and information exchange during innovation endeavours (Allen, 1977; Wheelwright & Clark, 1992). Effective uncertainty reduction imposes a need for reducing information asymmetries between the different partners involved in the innovation endeavour (suppliers, customers, beholders of complementary assets, and the different intra-company functional groups such as R&D, marketing and manufacturing).

However, there are some limitations to this approach as well. Several authors have argued that models of decision making under uncertainty often do not describe adequately real-world decision making (e.g. March, 1978; Daft & Lengel, 1986). They propose that often possible future outcomes are not identified or well defined and that there may be conflict with regard to what these will or should be. These authors state that decision-making and problem solving are often carried out under conditions of ambiguity, rather than uncertainty, where ambiguity is defined as lack of clarity regarding the relevant variables and their functional relationships. Ambiguity relates directly to Daft and Lengel's notion (1986) of equivocality, which they define as *"... ambiguity, the existence of multiple and conflicting interpretations about a situation."*

Allen already alluded to this in his 1977 book, when he explains why direct face-to-face contact is the most effective information channel in innovation settings. It is, he argues, because face-to-face contact does not only help to reduce uncertainty via the sharing of information, but more important still, face-to-face contact makes it easier to unveil and discuss divergences in interpretation on the information being shared. In other words, in an innovation context, we do not only have to consider situations of asymmetric information, but also, situations of asymmetric interpretation of information. In order to reduce asymmetries in interpretation, the richness of the information and information channels available therefore are of crucial importance.

As we all know, face-to-face information exchange carries a high level of media richness. As I will argue later on, three-dimensional parametric representations and models of product designs also carry a higher level of information richness than their traditional two-dimensional representations on calculation sheets and paper drawings. And, this is precisely where the design technology revolution comes in. Today, an increasing amount of technology is becoming available that allows for quick experiential design and development of three-dimensional representations of product forms. This implies that in fitting form to context of use via the development of the product design hierarchy, we now dispose of techniques that allow us to quickly define three-dimensional forms of the product (either on computer screen as happens with three-dimensional CAD systems such as CATIA, ProEngineer and Unigraphics or in hard models as happens with three-dimensional Rapid Prototyping technologies such as stereolithography and selective laser sintering).

These experiential forms can then be confronted with various stakeholders belonging to the context of use. In doing so, it becomes possible to define a new product form in a very experiential mode, consisting of cycles of iteration based on "real" representations of the product form. Moreover, taking into account the potential impact of new design technologies is also important to introduce and to emphasise the role of experiments during the innovation process. Many writings on managing the innovation process have almost exclusively focused on the issues of information and information exchange (see for instance the management of part-whole relationships as described by Van de Ven, 1986). However, as observed by Allen (1977), information exchange is (notwithstanding its importance), only a smaller part of the total activity of product designers and engineers. In Table 1, I summarise the activity patterns of designers and engineers in innovation projects as Tom Allen observed them.

Table 1: The importance of experiments during product design and development (Allen, 1977)

Source of time allocation	Percentage of total time allocated across 12 projects
Analysis and experimentation	77.3 %
Literature use	7.9 %
All communication (including literature)	16.4 %
Other activity	6.4 %
Total time reported (man-hours)	20,185 hours

As is clear from Table 1, analysis and experimentation make up for about 77% of the activity pattern of the designers and engineers involved in design and development. Sofar, we have largely neglected the organisation of these 77% in the context of innovation management. If we want to arrive at a more effective and efficient design and development process, we thus will have to better handle and understand the management of these analyses and experiments. In a very interesting and recent paper, Eisenhardt and Tabrizi (1995) argue that in complex product development projects (i.e. projects marked by high levels of ambiguity), traditional project management fails and should be replaced by experiential project management, consisting of a rapid sequence of design-build-test-redesign cycles.

This is precisely at the heart of the argument I want to make in this paper: in situations of high levels of ambiguity, when defining and designing a product form to fit the context of use, we will have to bring in modes of managing innovation projects that explicitly recognise the value and the contribution of experimentation and analysis. This however implies that we can arrive at experimentation strategies that move beyond mere trial and error experimentation. This is where the new design technologies come in as an integral part of managing the innovation process.

It is therefore the central thesis of this paper that these design technologies (I tend to call them meta-technologies or technologies to develop technology) add a new element to the management of the innovation process as they explicitly allow us to better manage cycles of experimentation in product definition and design to cope with both ambiguity and uncertainty. Ambiguity is thereby linked to reducing differences in interpretation on the product form (for instance, on the definition of the relevant space of functional parameters), while uncertainty is linked to arriving at acceptable target values for the chosen functional parameters via the reduction of differences in information on the context of use of the product form.

In other words, bringing in both ambiguity and uncertainty enables us to start managing more actively both product form definition (which is about the correct definition of the "problem" the product is about to solve) and product form creation (which is about solving the problems in order to successfully reduce the product definition to practice). In other words, we need a more intimate linkage between product definition and product creation. Or, as designers and developers often state: "once you have defined the problem you want to solve, you have solved it." And, the specific way to manage this intimate linkage between problem definition and problem solution is via the effective management of analysis and experimentation. This is where the new design technologies start perhaps slowly but firmly occupying their place and space in the innovation environment of the firm.

2. Managing innovation processes: fundamental insights

Decades of research into the management of innovation processes have led to the discovery of fundamental critical success factors (for a good summary overview, I refer to Tidd, Bessant & Pavitt, 1997). In order to revisit them from the perspective of the impact of new design technologies, they are now briefly summarised.

2.1. Explaining the core of innovation performance

In Figure 1, I provide a (simplified) summary overview of the key performance variables relevant for the innovation process at the operational level. The critical influence of information flows and communication patterns on the performance of innovation activities has been well-documented and subject to major research attention (see Brown and Eisenhardt, 1995, for an excellent overview of the different research studies on this topic). These flows are at the heart of the summary performance model. The attention paid to information flows and communication networks is not astonishing given the need for uncertainty reduction during the innovation process, as described in the previous section. As Tom Allen noticed in his early work (1977): information is the primary input into any process of uncertainty reduction.

Not only is there a need for intense intra-organisational and cross-functional information flows and communication patterns during the innovation process; but, also for the innovative organisation to be well embedded and linked to its broader (external) technological environment. This embeddedness is symbolised by the presence of special 'network' roles during the innovation process, amongst which the gatekeeper figures prominently (Allen, 1977). Related studies that have their origins in the development and the marketing of new products have further pointed to the importance of:

(1) appropriate modes of work organisation (amongst which project structures figure predominant), and
(2) design methodologies (such as Quality Function Deployment),

in order to achieve a high performing innovation process (Cooper, 1993; Crawford, 1983; Wheelwright & Clark, 1992).

The methodological avenues that have received ample attention include:

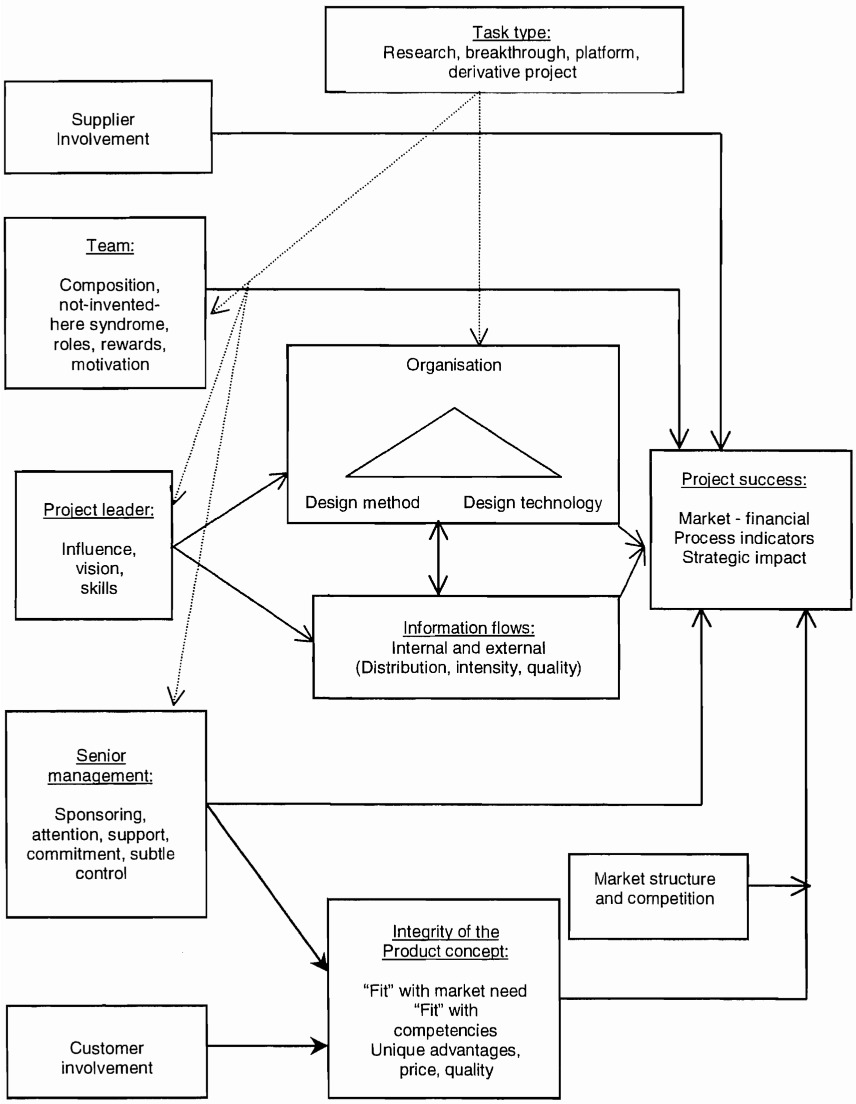
- the use of flowchart-based decision and monitoring models of the innovation process (e.g. the phase models and stage-gate models as described in Souder, 1987 or in Twiss, 1994) taking into account both the fuzzy front end phase of every innovation endeavour as well as the need for learning between projects as manifested by the presence of a "post"-project phase (Debackere & Vandevelde, 1996; Deschamps & Nayak, 1995);
- the introduction of creativity-stimulating and idea-generating techniques like brainstorming and mind-mapping (e.g. Povel, 1993, Terninko, Zusman & Zlotin, 1998);
- the use and the design of grid-methodologies and techniques to identify, to define and to monitor innovation opportunities (e.g. swot-assessments, product maturity grids, business growth matrices, quality function deployment matrices; I refer to Clark & Fujimoto (1991) as well as Wheelwright & Clark (1992) for a good overview);
- the development of selection methodologies that respond to the innovation's need for funnelling, i.e. filtering and tunnelling a wealth of ideas into a more limited set of new product-technology concepts toward a still more limited set of "successful" products (for an excellent overview of the funnelling concept, I refer to Wheelwright & Clark, 1992);
- the application of project management techniques to follow-up on innovation endeavours (see for instance Duncan, 1996).

The interaction and co-evolution of work organisation, design methodologies and information flows are at the very heart of the operational management of the innovation process. As can be seen from Figure 1, the advent of design technologies such as tree-dimensional computer aided design systems and rapid prototyping as well as rapid tooling techniques adds yet another dimension to the heart of a high-performing innovation process. As argued in the previous sections, the advent of these technologies has a dramatic impact on the principles of concurrency and time-compression that at the moment represent a key trend in the management of new product development processes (Loch & Terwiesch, 1998).

They are instrumental in making "experimentation" a central activity during any innovation process. By their very nature, the new design technologies assist to integrate the new product development process to allow participants making upstream decisions to consider downstream and external requirements, including the timely and relevant involvement of downstream and external decision makers.

Information flows are mediated and supported by an appropriate work-organisation format and design methodology. However, in order for these modes of organisation and design methods to be deployed successfully, the necessary informal as well as formal information flows and communication patterns have to be put in place and have to be sustained. Hence, there is an immediate, two-way interaction between structural variables such as organisation, design methodology and design technology on the one hand and information flows on the other hand. This two-way interaction is at the heart of the process of ambiguity and uncertainty reduction discussed earlier on. This two-way interaction is at the heart of what I will call later on the "Integrated Design Capability" of the innovative firm.

Figure 1: An integrated model of innovation project performance



2.2. Innovation performance as a multidimensional concept

As further shown in Figure 1, innovation performance is a complex and multi-dimensional construct. Performance relates to such rational, financial indicators as market shares and revenues that accrue from innovative activities. However, market shares and revenues only present one dimension of the performance concept. The second route toward measuring performance refers to the internal efficiency of the innovation process. It considers the extent to which the innovation process is efficiently managed in terms of, for instance, throughput times during the various phases of the innovation trajectory (e.g., time-to-concept, experimental problem-solving cycle times, time-to-ramp-up). A third type of performance dimension relates to perceptual measures as the innovation's contribution to the strategic mission of the organisation.

It is important that we accept the multidimensionality of the performance construct. Early studies on innovation performance have indeed focused quite heavily on the market and financial performance indicators. Even today, many project management techniques that are used to follow-up on innovation projects still use this rather monolithic approach. In an era where the capability to quickly learn from failure and experimentation is probably one of the hallmark characteristics of successful innovators, the traditional, rational performance approach may be dangerous, as it tends to focus on single-loop learning rather than double-loop learning.

2.3. Antecedents of innovation performance

The above dimensions of innovative performance (often operationalised at the project-level and aggregated at the portfolio-level) are influenced and leveraged by a myriad of parameters, as is further shown in Figure 1. As mentioned, communication patterns, information flows, and work organisation techniques are at the core of this framework. In addition, there are important roles to be assumed.

Senior management attitude and commitment, project leader traits and behaviour, as well as team member characteristics exert a strong influence on the performance of innovation activities. Moreover, these have to be embedded in an appropriate motivational context, using incentive mechanisms that foster "project ownership" rather than "performance control." Incentive mechanisms fostering entrepreneurship and "ownership" in innovative contexts therefore have to be related to the project process (Philips goes as far as calling the project process a Business Creation

Process rather than a Product Creation Process) as well as to the overall success of the project in the eyes of its customer (e.g., by providing substantive bonus-schemes for the project members if they achieve a successful project result). Of course, as suggested in Figure 1, the complexity of the project (research versus breakthrough, platform or derivative as defined by Wheelwright & Clark, 1992) has an important impact on the relationships just described. More specifically, in the case of derivative or incremental projects, these performance relationships can be managed in a much more structured and formalised way than in the case of a research activity or a breakthrough project. For instance, in a breakthrough project, creating ownership may involve the development of highly visible bonus schemes that give the project members significant stakes in the project's success. For derivative projects this should not be the case. Here the incentive system should evaluate such 'classic' performance control criteria as responsiveness and timeliness of the project members' activities.

The involvement of external parties, more specifically suppliers and customers, is yet another well-known determinant of innovation success (see for instance Eric von Hippel's research on the role of lead users during the innovation process (1988)). The relative importance of their impact varies depending on the party that obtains the highest returns from investing in the innovation. Although this is a simple criterion, it may be hard to realise who will benefit most from a particular innovation, certainly when it pertains to emerging technologies and industries.

For example, the telecommunications industry is in full flux. Product and service innovations are increasingly intertwined and have a dramatic impact on our daily life. However, it is unclear so far who will reap the most benefits from those innovations. Five years ago, MCI was a big innovator in the industry. Today, it has been acquired by WorldCom, which is much smaller than MCI but is now one of the most admired service innovators in the industry. However, it is still not clear whether a company like WorldCom will ultimately be able to reap the benefits from those innovations, or whether they will accrue to another as yet unknown player in the industry. For instance, what about "traditional" telecom companies like Lucent and Alcatel? Hence, it is only when the "new" constellation of added values due resulting from the innovation can be articulated, that we can start analysing who should benefit most from involvement in the innovation process. In emerging industries, this value constellation is most often unclear, and hence the relative importance of users and suppliers is difficult to establish.

As can be seen in Figure 1, the structure of the market or the degree of competition in the marketplace are other important parameters influencing success along the innovation journey. Turbulent market structures, marked by high degrees of monopolistic competition, strongly moderate the “optimal” organisation of the innovation process. Examples abound, such as the case of Quantum Corporation. Quantum, active in the area of computer disk drives, experienced a turbulent, fast-evolving marketplace with fierce competition based on slightly differentiated product characteristics.

This competitive environment necessitated an innovation function that is highly responsive to frequent changes in the marketplace. As a solution, Quantum based the organisation of its innovation process on flexible lateral (team-based) structures, state-of-the-art functions or competencies, and appropriate incentive systems. These required each team member to act as a “cross-functional specialist” (which of course may seem like a contradiction in terminis). As those “cross-functional specialists” had to strike a balance between team performance versus individual performance as well as between expertise and experience, appropriate incentive systems were developed and implemented.

This need for “cross-functional specialists” points to the dilemma or the tension present in the innovation matrix; an organisational tension which is characteristic of most innovative companies. Any innovator needs to balance the development of competencies (i.e. the development of a sufficient absorptive capability) with the imperative to achieve the results expected from the projects and programs in the portfolio. Creating a matrix form of organisation structure, in which competence areas and project teams are intertwined and balanced, often captures this dilemma. As shown in Table 2, the successful innovation organisation requires a matrix structure balancing a clear division of influence, power and authority between its project management component and its competence management component.

In order for competencies to be allocated to and deployed in a breakthrough or platform project, they need to be up-to-date and state-of-the-art (we intentionally leave out derivative projects, since they often require only minimal forms of project organisation). Hence, successful breakthrough and platform projects will have to be embedded in strongly developed competence areas. This calls for a “strong” matrix structure, where competence areas and project management both are allies in resource accumulation and deployment, rather than the one being dominated by the other. Both components of the matrix structure have to be state-of-the-art in their respective domains of expertise and experience. It is obvious that this presence of two strong components carries the germs for a situation of conflict.

Table 2: Project performance in the innovation matrix (Adapted from Katz & Allen, 1985)

Locus of decision-making on organisational issues	**Locus of decision-making on competence issues**	
	project management dominates competence management	**competence management dominates project management**
project management dominates competence management	moderately positive performance	strongly positive performance
competence management dominates project management	average performance	strongly negative performance

This, though, need not be a problem since a "strong" matrix certainly is not free from conflicts between its project and the competence components. But, what a "strong" matrix certainly does have, is an ability to solve those conflicts. In other words, "strong"-matrix forms of organisations handle the tensions that occur between their competence and project components not by being conflict-free, but through their ability to manage and resolve the conflicts that inevitably occur. This is a critical capability in managing innovation matrices. Certain companies, such as Intel, have become very good at it.

This argument is further corroborated by the research results reported in Table 2. Two major dimensions that relate to decision-making in an innovation matrix have to be dealt with. First of all, decisions about competence issues will have to be made. These are, for instance, decisions relating to technical issues such as the telecommunication protocol to be used in the development of a new product. Will it be the Internet protocol TCP/IP or not? Second, decisions have to be made with respect to organisational or managerial issues. These decisions pertain to such questions and topics as the allocation of (additional) resources to a project or the evaluation of the performance of project team members.

For each of those decision areas, we have to ask what should be the most influential component. Should it be the competence component of the organisation, or should it be the project component? The summary research results reported in Table 2 show that the highest performance is obtained when a balance is realised between the competence and the project component. The project component then dominates organisational/managerial decision-making; while the competence component dominates competence-related or technical decision-making. The lowest performance occurs when the competence component dominates both organisational/managerial decision-making on the project and technical decision-making on the project. In the other instances (see Table 2), project performance is average or moderately positive.

Thus, the tension in the innovation matrix calls for competencies and projects to be both well managed and state-of-the-art, instead of one "unilaterally" dominating the other. Unfortunately, since organisations have (and always will have) limited resources available, this important finding is often obscured. Very often, the finite capacity problem is solved by allowing one component in the innovation matrix to gain complete control over the other component on both dimensions of the decision-making process. This, however, leads to sub-optimal performance as demonstrated in Table 2.

Still worse, all too often the finite capacity constraints are resolved by making the traditional functional (i.e. the competence based) organisation dominate decision-making along both dimensions. As is demonstrated in Table 2, this is the worst case scenario. Typically, in such a situation, it becomes impossible to grow and to retain strong project management skills and leadership. The overall result is an innovation project management function that underperforms and does not achieve its objectives in terms of strategic support to the growth of the company.

3. Boeing: a case study on the use of technologies to develop technology

Boeing has received much attention as an example of the application of new design technologies (Sabbagh, 1996). Throughout its history, the company has demonstrated a capability for both product and process innovation that turns it into an interesting case study subject, either as a pioneer or a follower. Boeing is known for the rigor with which it has come to apply project management principles throughout its development and manufacturing process. As it comes to product development, Boeing is reputable for designing platforms or families of aircraft. This design flexibility allowed for several variations, drawing on the same base airframe concepts. Modifications such as a stretched fuselage to increase capacity can thus be accommodated without wholesale revisions in design or the need to start up entirely separate development programs. The company has also been a pioneer in building co-development and outsourcing relationships. More recent, Boeing became a role model in applying concurrent engineering principles and new design technologies to the design and development of the 777 aeroplane.

3.1. Gearing up for a (r)evolution in aircraft design: setting the stage for the 777

Like many inventions, the turbojet aeroplane engine was developed more or less simultaneously and independently by different individuals in different parts of the world (Constant, 1980). This simultaneous character of the inventive process has been well documented (for an excellent insight, I refer to Merton's discussions on singletons and multiples in scientific discovery). In England, Frank Whittle developed the idea of using jet propulsion in aircraft and applied for his first patent in 1930. In Germany, almost simultaneously, another researcher, Hans von Ohain, started his development work on jet propulsion. The result of their efforts was the emergence of the jet aircraft at the end of the Second World War. Communities of practitioners emerged and coalesced on the design and further development of the turbojet engine (Constant, 1980). It is interesting to note that, in 1991, Whittle and von Ohain were the second recipients of the prestigious Draper Prize by the United States' National Academy of Engineering for their contribution to modern aircraft development. The first Draper Prize was awarded in 1989 to Jack Kilby and Robert Noyce for their independent roles in inventing and developing the integrated circuit (Petroski, 1996).

Because of Germany's post-war economic problems, the turbojet aircraft first took off in the United Kingdom. During the 1950s, turbojet aircraft suffered fatal failures. This triggered a serious investigation of the plane's design. At first, pilot errors and bad weather were considered the major culprits. However, in the end the cause was identified as metal fatigue. This was a new phenomenon in aircraft.

Before the introduction of jets, aeroplanes did not fly so high and thus did not have to be so highly pressurised for passenger comfort. In order to gain the fuel efficiency that gave the new engine part of its advantage, jets had to fly higher than propeller-driven aircraft. As they did, the structural components of the aircraft were subjected to conditions that were beyond the experience of its designers. Previously, metal fatigue was believed to affect only machine parts that were subjected to cycles numbering in the thousands, or even millions. Therefore, aircraft engineers did not believe that fatigue would affect a plane, as it would be subjected to many less cycles during its lifetime. However, the aeroplane fuselage, as it alternates between no net pressure difference when the plane is on the ground and a net internal pressure as it flies at high altitude, is subject to fatigue.

As it took quite some time to the engineering community to figure out these problems, planes lost the confidence of the flying public. As a consequence, the British aircraft industry lost its advantage and other companies, especially in the United States, began to develop their own aircraft models. Boeing, Lockheed, McDonnell and Douglas (later McDonnell-Douglas) were the major players. The American aircraft engineers got a head start as they learned from the failure of their British colleagues. Over the years, the Boeing company came to dominate the world market for commercial jet aircraft. This competitive advantage was mainly due to its highly reliable 707 plane (Petroski, 1996; Sabbagh, 1996). As air travel increased and as fuel prices became a significant fraction in the operating cost of airlines, a variety of competing commercial jet aircraft emerged.

As early as the mid-1970s, the European Airbus consortium began challenging the American dominated aircraft industry. By the mid-1980s, Airbus had become a recognised player on the world commercial aircraft market. As a consequence, by the late 1980s, Boeing began to look to design a new aircraft that would fill needs that planes like its 747 and 767 did not. More specific, Boeing needed to fill a “gap” with respect to seating capacity and range of its commercial jets keeping in mind economic development in the Pacific Rim area. The company needed a large body aircraft able to cover distance ranges between 7,000 and 8,000 nautical miles.

At first Boeing thought of stretching the existing 767 design. This would be a safe, quick and low-cost way of providing a plane with an increased seat capacity. In the meantime, though, both McDonnell-Douglas and Airbus were expected to offer new large capacity, long range aircraft. With such competition in view, Boeing decided that it would be better to develop a plane that could compete in a more direct way with the new competition. After United Airlines provided a firm “base load” order for the new plane, Boeing was able to launch its 777 design in the second half of 1990.

In order to better the “fit” between form and context, Boeing invited eight airlines to get involved with the design of the 777 in the early conceptual design phase, when little of the design parameter space was firmly decided upon. This allowed for taking into account customer requirements. Although eight airlines had to agree upon some basic design concepts (an almost impossible job to accomplish), Boeing was able to work toward a consensus with them that enabled its engineers to arrive at a solid basis for more detailed engineering work.

3.2. Designing a plane

In traditional aircraft design, many engineers and draftspersons work individually and in team on various parts and subsystems of the plane. As explained in detail by Petroski (1996), there were over 130,000 unique individual parts to be engineered in the 777, and when rivets and other fasteners were counted, over 3,000,000 parts were to be assembled in each plane. The 747, which had a total of 4,500,000 parts, required about 75,000 individual drawings to specify. This great number of drawings all had to be internally consistent if the various parts and subassemblies were to fit. This required a lot of interface work between engineers. Whenever a design change occurred, all drawings had to be checked in order to assess its impact and to adapt the existing design to the new one. This obviously was a slow and tedious process.

Even with lots of checking, cross-checking, and double-checking, human error could never be totally excluded and as a consequence, mismatches occurred frequently. In order to trace incompatibilities across parts, subsystems and systems, physical prototypes were built. This approach was of course expensive and time-consuming. In the past, Boeing had tried to minimise these problems through an intensive quality management approach emphasising the need for intensive co-operation throughout the design process.

In order to remedy the aforementioned drawbacks, Boeing opted for a paperless design of the 777. Computers would be used in the design, testing and manufacturing process to a greater extent than ever before. Three-dimensional CAD systems would prove to be the solution to this challenge, enabling Boeing to achieve maximum concurrency during the design of the new plane while at the same time aiming at a high-quality robust design.

Boeing already developed some experience with CAD when designing engine parts of the 767. Both from a cost and throughput time perspective, the CAD approach proved a significant improvement over the traditional "drawing" and "interfacing" approach. Also, Boeing had experienced a sharp decline in Engineering Change Orders once the 767 CAD designs were released. The CAD system used during this pilot was the Computer Aided Three-dimensional Interactive Application (CATIA) developed by the French software firm Dassault Systèmes.

In order to be useful for the design of the 777, the CATIA system had to be scaled-up, which was in itself a major engineering effort. Just some numbers to illustrate the task at hand. Total storage capacity for the overall system reached 3.5 terabytes (the equivalent of 2,500,000 million 3.5-inch high-density disks). As many as 238 teams, including up to 40 engineers, were involved in the design, development and manufacturing of the 777. All engineers needed access to all of the computer data. A paperless design meant that instead of waiting for drawings, any engineer working on any part or subassembly could call up all connected parts and subassemblies on any library of the 7,000 workstations that were scattered across 17 time zones. In order to make this possible, Boeing laid dedicated data lines across the Pacific Ocean. About 20 percent of the fuselage structure was being designed and developed by a consortium of Japanese partners including Fuji, Kawasaki and Mitsubishi Heavy Industries. Their engineers had to be logged into the worldwide 777-workstation network.

Via an electronic pre-assembly program, interference between parts and systems was continuously identified. To be sure that the newly developed CAD-system was itself reliable, an integrated prototyping strategy was developed. As soon as possible, physical prototypes of aircraft subsystems were developed that allowed checking the design rules that rolled out of the CATIA system. In addition, Boeing developed a simulated mechanic, CATIA-man, who could be manipulated to crawl around inside the assembled digital plane to check manoeuvrability during construction and maintenance operations.

3.3. The design revolution

The Boeing example clearly illustrates the fundamental change in the design process that began in the United States during the 1980s. This change was brought about as the result of several pressures, including:

- market pressures due to globalisation trends,
- decreasing lifecycles of consumer products and high-tech products,
- the need to shorten product development times,

- the need to improve product quality and,
- the need to improve communication between design and development engineering on the one hand, and manufacturing and customer-centred marketing on the other hand.

A major theme underlying all these pressures often is an obsession with the customer, as nicely described in Treacy and Wiersema's best-selling book "The Discipline of Market Leaders" (1996). This customer intimacy requires new modes of organisation, new design methods and new design technologies that enable concurrency, overlap and co-realisation of the new product in an intimate co-operation between internal departments at the company and customers or suppliers. As a consequence, the keyword for the design revolution we witness at present is improved communications.

These improved communications, and the "virtual" and "physical" visualisations that accompany them because of the three-dimensional parametric character of most new design technologies (just think about CATIA-man), are ideal vehicles to help reduce both the ambiguity and the uncertainty that underlay all new product development trajectories. This is possible because of the potentially "rich" character of the information that becomes available via the use of the 3D technologies, thus benefiting the reduction of information as well as interpretation asymmetries. Moreover, as argued earlier, these technologies can be at the centre of the development and management of fast experimentation strategies that result in highly effective cycles of design-build-test-redesign that are crucial in fitting product form to its context of use (Debackere, 1998; Loch & Terwiesch, 1998; Thomke, 1997). This, of course, brings us to the need to define the new design environment that fits today's innovation imperatives.

4. The new design environment: organisation, methodology and technology

Design technologies have occurred in many different application areas. Although their history and variety is most well established in mechanical applications, they start making significant inroads into other areas as well (e.g. rational or structured drug design and molecular modelling in pharmaceuticals, simulation and testing of circuitry in electronics). In this section, we reflect on the benefits and the pitfalls in introducing this new design environment.

As explained previously in Figure 1, new design technologies are one of various central components that are at the core of determining innovation performance. These design technologies, as illustrated in the Boeing case, have as unique attributes their potential information richness because of the 3D (visual) character of the information they provide as well as their contribution to quick cycle experiential development strategies since they allow for fast iterations of analysis and experimentation. Without going into detail on the huge variety of design technologies available today, I just want to mention their increasing inroads along and across all functional areas that intervene during an innovation effort, from product design over prototype creation to rapid development of process tooling.

4.1. A collection of technologies

In the engineering literature, the amount of information and evidence on the potential impact and the use of new design technologies are tremendous (e.g. Ertas & Jones, 1996; Jayaram, 1995; McMahon & Browne, 1993; Van der Schueren & Kruth, 1996). In this brief summary, I just want to highlight some of the major features and characteristics of those technologies, without of course entering into all the technical details of the tools and techniques involved.

First of all, the advent and the presence of analytical techniques that allow for 3D visual representations and simulations of product concepts linked to such calculations as kinematic modelling, dynamic modelling, stress modelling and thermal modelling has a direct impact on the product design phase of the innovation process. One of the basic mathematical techniques supporting this evolution has been Finite Element Analysis. It has become the primary tool in stress analysis and structural dynamics, and the ability to adapt it for use with CAD has contributed greatly to the proliferation of CAD systems in industry. Because of its parametric character, Finite Element Analysis can be used in analysing designs involving varying geometric shapes as well as non-homogeneous materials. It also provides considerable flexibility in the setting of loading and support conditions. It is also used in the solution of heat transfer problems and the analysis of fluid flow and electrical and magnetic fields.

Although 2D draftings continue to be the most widely used CAD application, many manufacturing firms have chosen to shift to solid 3D modelling. Solid modelling provides a complete geometric and mathematical description of part geometry, which is important if the model is to be used for design analysis, simulation, generation of mass properties, or for developing NC (numerically controlled) data to machine the part. Thanks to advances in hardware and software, it is now possible to use 3D representations instead of 2D or 2.5D, or wireframe models. The 2.5D representations are 2D renderings that include thickness data for some regions of the 2D part. Unlike surface representations that use points, lines, and curves to define an object, solid modelling uses elements such as boxes, cones, cylinders and manipulated 2D shapes to generate models. The IGES standard (Initial Graphics Exchange Standard) allows 2D systems to transfer data between different vendors. Solid modelling can be used for various purposes, such as creating realistic visual displays, analysing the motion of components (including interference with other elements, see for instance the Boeing example), and structural analysis. The greatest advantage that solid models offer over surface models is enhanced integration of design and manufacturing.

A few examples of Computer Aided Design (CAD) and Computer Aided Engineering (CAE) tools are AutoCad®, ProEngineer®, PTModeller®, ProMechanica®, CATIA®, Unigraphics® or Mentor Graphics® (in the case of electronic designs). They can be directly linked to, for instance, product data management tools such as CADIM® that allow for building complete libraries of the product's design hierarchy that can then become available to manufacturing and operations, for instance as Bill-of-Materials.

Second, a variety of physical techniques allow for the rapid development of 3D physical prototypes and tools. For instance, just to name a few, stereolithography, selective laser sintering, laminated object modelling and manufacturing, holographic interference solidification, photochemical machining, selective area laser deposition, selective metal powder sintering, fused deposition modelling, multiphase jet solidification, ballistic particle manufacturing, direct shell production casting, etc. Rapid prototyping (and tooling) techniques thus produce physical models from CAD data either by material layer deposition or (also increasingly today) by material layer removal.

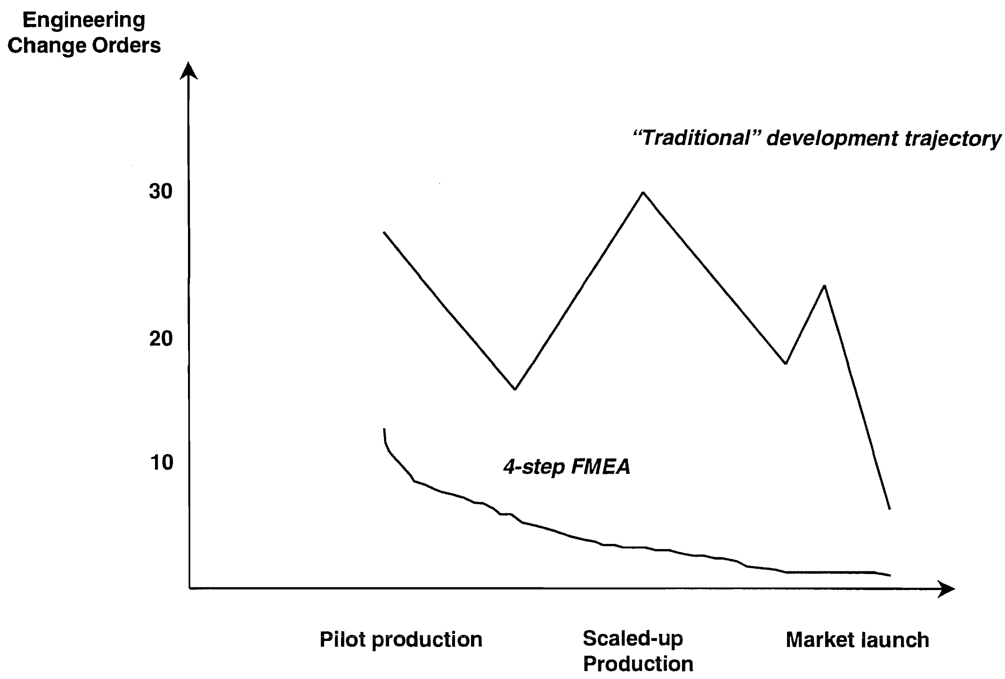
Most rapid prototyping systems electronically divide a 3D CAD model of the part into thin horizontal cross-sections and then transform the design, layer by layer, into a physical model. Rapid prototyping (and tooling) techniques are increasingly being used during the product development cycle. For instance, Ford Motor Company uses stereolithography as an integral part of concurrent product and process design. Developing new automobile components is expensive, traditionally requiring many design iterations and significant schedule time. Stereolithography allows the production of models of the part in a single day, using the same CAD data needed for structural analysis, kinematic studies, NC programming, etc. An example of the use of this technology occurred when Ford sought a supplier for a newly designed internal combustion engine rocker arm. When different suppliers had difficulties in interpreting the 2D drawings of the rocker arm, Ford turned to stereolithography to produce a model of the part in one day. When the model was made available to bidders Ford received a quote that saved up to 3 million US$ annually in production costs.

Although rapid prototyping and tooling technologies are evolving at great speed, there are of course still limitations as to their use. These include limitations due to the use of rapid prototype materials different from those specified for the part being designed, restrictions on the number and variety of test conditions that can be applied to the prototype, and difficulty in using test data from the prototype in performing Finite Element Analysis. In addition, even if the tools are available, our own research shows that it takes some time and change of mindset before designers and engineers are able to make the switch to the new design approach. Training and developing familiarity with the new tools is crucial. However, even when training and guidance are provided, it takes time before the tools are being used in an effective and an efficient manner. Moreover, it is obvious that the introduction of those new design tools may have a quite disruptive impact on the "established" design expertise and experience at the company. As a consequence, "Not Invented Here" syndromes and resistance to change phenomena may well occur and may thus put a strain on the deployment of the new tools and techniques.

To conclude this brief overview, virtual prototyping is a term that describes the computer analysis and testing of CAD models before the commitment is made to produce the physical prototype. In virtual prototyping the CAD model is evaluated by iterative dynamic simulation before making the physical model. This technique allows testing of the model under various kinematic and dynamic conditions that would be expensive and complex to duplicate in the laboratory.

These last reflections suggest that the use of virtual and physical prototyping should be intertwined and integrated. In our recent research, we therefore are now attempting at establishing a model for the design of "optimal prototyping strategies" as an integral part of the experimentation and analysis strategy used during the new product design process. These optimal prototyping strategies aim at using virtual and physical prototyping in an intermittent and iterative manner in order to arrive at an intelligent experimental program. In this way, the organisation of the design process becomes a rapid sequence of design-build-test-redesign cycles. The "build" phase of the cycle then uses the prototyping approach that offers most added value in terms of design changes and improvements (or for that matter, elimination of design errors) at any moment during the design process.

Figure 2: Impact of new design technologies on Engineering Change Order patterns at one company (Debackere, 1998)



In one of the companies that participated in this research, the development of such an experiential prototyping strategy has been called the 4-step FMEA (Failure Mode and Effect Analysis) process during product design. In this 4-step FMEA process, drawings, 3D CAD models and simulations, and physical prototypes are used and integrated in a concurrent design process. The intermittent use of virtual and physical models allows maximising the elimination of design errors, both from a product functional design perspective and from a process engineering perspective. The results of this integrated experiential prototyping strategy have proved to be quite significant. In Figure 2, for instance, a summary overview of the evolution in number of Engineering Change Orders (ECOs) shows the drastic improvement realised via the introduction of virtual and physical prototyping strategies during the 4-step FMEA process. The traditional approach did not use this "intelligent" intermittent deployment of the various design technologies discussed above.

Finally, in Tables 3 and 4, some empirical results on the impact of the use of new design technologies on innovation performance indicators are presented. The impact on design and development capacity, cost and throughput time is obvious.

Table 3: The impact of 3D CAD technologies on transformer design (Debackere, 1998)

Performance Indicators	"Traditional" design environment (spreadsheet calculations and 2D CAD)	"New" design environment (3D CAD with integrated electromagnetic calculations)
Average calculation time per transformer	110 hours	15 hours
Average drawing time per transformer	400 hours	210 hours
Other activities	160 hours	100 hours
Total yearly capacity in design department for 280 transformers totalling 9109 MVA	65	33

However, the results obtained by Stefan Thomke (see Table 4, 1997) still point to another phenomenon that was also observed already by Eisenhardt and Tabrizi (1995). In his research, Thomke compares the use of Electronically Programmed Logic Devices (EPLDs) to Application-Specific Integrated Circuits (ASICs) during the design and development phase in IC design. While ASIC technology has been available to designers for more than a decade, EPLDs are a relatively new technology. They were invented in the late 1980s and have rapidly improved since then.

Table 4: The impact of new prototyping technology on IC development (based on Thomke, 1997)

Process Indicator	EPLD design technology (47 projects)	ASIC design technology (31 projects)	p-value
Number of prototype iterations	14	1.5	< 0.001
Throughput time	8 months	18 months	< 0.01
Cost of prototype change	Less than 100$	More than 10,000$	---
Time required to change prototype	Less than 1 day	More than 1 week	---

As is evident from Table 4, the use of EPLDs does not only lead to a significant improvement in innovation performance. But, it also enables the designers to dramatically increase the number of prototypes used during an innovation project (up to 14 prototype iterations instead of an average of 1.5 for ASIC design technology). This puts a strain on "traditional" phased project planning approaches as it almost becomes impossible to have detailed milestone planning and reviews in this fast prototype design and change cycle approach. In other words, the "traditional" (phased and planned) project organisation format is being replaced here by a more adaptive approach. This adaptive approach allows for a quick sequence of experimentation and analysis cycles, as extensively described in the previous sections of this paper. Eisenhardt and Tabrizi (1995) coined this organisational approach as "experiential project structures."

4.2. The Integrated Design Capability

By now, it has become obvious that companies that want to deploy innovation in support of their competitive position might consider investing in an Integrated Design Capability that supports a fast-cycle design process. This Integrated Design Capability "fuses" organisational approaches (traditional and experiential project structures, competence versus project organisation in the innovation matrix), design methodologies (such as Quality Function Deployment) and the aforementioned design technologies into one consistent support infrastructure for a company's innovation process. This, of course, implies a serious investment and hence, becomes a strategic decision for the organisation. It also implies a clear strategic choice toward which market segments and application areas the company decides to turn its innovation attention. This is mainly because investments in design technologies are not completely application-independent, as illustrated with the arguments and discussions in the previous sections.

The Dutch steel and aluminium company, Koninklijke Hoogovens, has developed two Integrated Design Centres over the last years: the Centre for Packaging Technology and the Centre for Product Applications in Transport and Building Applications. Each of those centres creates and sustains an environment in which appropriate organisational approaches, combined with a set of design methods and techniques, are geared toward an effective and efficient innovation process.

To conclude, in Table 5, I present some of our recent research results that illustrate how various dimensions of an Integrated Design Capability influence one specific innovation process performance indicator, namely the smooth introduction of new product designs into manufacturing operations. The statistical analyses reported are based on an extensive questionnaire and interview survey of 103 innovation projects at Flemish companies over the period 1996-1997, with special attention being paid to the organisation of the interface between design and manufacturing.

As is obvious from the four regression models discussed in Table 5,

- communication (both formal and informal),
- and the degrees of freedom for experimentation and learning,
- and the organisation of the innovation process,
- and the use of new design technologies

all have a significant and positive impact on the process performance indicator analysed. These empirical results therefore provide further corroboration for the examples, arguments and hypotheses developed in the various sections of this paper.

Table 5: Regression results explaining the performance of introducing new product designs into manufacturing operations (based on Debackere, Vandevelde, Van Dierdonck, 1998)

Dependent Variable =
Smooth introduction of new product designs into manufacturing operations
(D.V. based on survey scale, range 0 (not smooth at all) -to- 10 (extremely smooth))
(Survey of N=103 new product development projects)

Model I:

D.V. = 9.50 + 0.64 x (use of design technologies) – 0.70 x (level of task complexity)

Adj. $R^2 = 0.25$, p-value model < 0.001, b-coefficients significant at .05-level or below.
Independent variables were the result of factor analyses and multiple item scales.
They are always coded from low to high.

Model II:

D.V. = 8.35 +		8.34 x	(intensity of informal communication between design, development and manufacturing)
	+	0.72 x	(intensity of written, formal communication between design, development and manufacturing)
	-	0.45 x	(level of task complexity)

Adj. $R^2 = 0.32$, p-value model < 0.001, b-coefficients significant at .05-level or below.
Independent variables were the result of factor analyses and multiple item scales.
They are always coded from low to high.

Model III:

D.V. = 6.62 +		1.10 x	(degree of formal organisation during design and development process)
	+	0.67 x	(organisational involvement of developers during manufacturing ramp-up)
	+	0.84 x	(formal planning and execution of pilot runs and prototype testing)

Adj. $R^2 = 0.39$, p-value model < 0.001, b-coefficients significant at .05-level or below.
Independent variables were the result of factor analyses and multiple item scales.
They are always coded from low to high.

Model IV:

D.V. = 6.74 +		1.15 x	(familiarity of product developers with manufacturing operations)
	+	0.50 x	(room for experimentation and learning during design and development)

Adj. $R^2 = 0.27$, p-value model < 0.001, b-coefficients significant at .05-level or below.
Independent variables were the result of factor analyses and multiple item scales.
They are always coded from low to high.

5. Conclusion

In this paper, we have attempted at providing an insight into the major components of the "new" integrated design environment that companies can deploy to support their innovation process. Core concepts that have been discussed in support of our arguments in favour of the integration of new design technologies into a systematic approach of the innovation process were ambiguity, uncertainty and learning via experimentation and analysis. Of course, as argued, implementing an Integrated Design Capability is not without difficulties and problems.

As mentioned, introducing an integrated design capability in an organisation may be quite disruptive with respect to the design expertise and experience currently available. However, the new design environment also allows for a more adaptive and responsive interpretation of the "traditional" (phased and planned) project management structures that have been deployed in innovation contexts in the past.

To conclude, in Table 6, a detailed summary on the organisational, methodological and technological components of an Integrated Design Capability is provided.

Table 6: The Consensus Set of 56 "Best Practices" by Category (ASME Council on Education, 1995) during the Product Realisation Process (PRP)

Knowledge of PRP	PRP team skills	Design skills	Analysis & testing skills	Manufacturing skills
1. Knowledge of product realisation process 2. Bench marking 3. Concurrent engineering 4. Corporate vision and product fit 5. Interface with other business functions (marketing, intellectual property & legal, ...) 6. Industrial design	7. Project management tools 8. Budgeting 9. Project risk analysis 10. Design reviews 11. Information processing 12. Communication 13. Sketching/ drawing 14. Leadership 15. Conflict management 16. Professional ethics 17. Teams/ teamwork	18. Competitive analysis 19. Creative thinking 20. Tools for "customer-centred" design (QFD-HoQ) 21. Solid modelling/ rapid prototyping and tooling systems 22. Systems perspective 23. Design for assembly 24. Design for commonality platform 25. Design for cost 26. Design for disassembly 27. Design for environment 28. Design for ergonomics (human factors) 29. Design for manufacturing 30. Design for performance 31. Design for reliability 32. Design for safety 33. Design for service/repair 34. CAD systems (2D & 3D) 35. Geometric tolerancing	36. Finite elements analysis 37. Design of experiments 38. Value engineering 39. Mechatronics (mechanisms and controls) 40. Process improvement tools 41. Statistical process control 42. Design standards (e.g. UL, ASME, IEC, ANSI) 43. Testing standards (e.g. ASTM) 44. Process standards (e.g. ISO 9000, AQAP) 45. Product testing 46. Physical testing 47. Test equipment 48. Application of statistics 49. Reliability	50. Materials planning inventory 51. Total quality management 52. Manufacturing process 53. Manufacturing floor / work cell layout 54. Robotics and automated assembly 55. Computer-integrated manufacturing 56. Electro-mechanical packaging

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